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Some Components of an Ecosystem Model of Westernport Bay

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Abstract: This paper describes the present structure of the Westernport Bay Water Quality Model, some preliminary results obtained from its use and proposals for future extension and application of the model.

The model has been developed to enable the waters of the Bay to be managed to best effect. The pollutant levels resulting from a given waste disposal strategy may be examined for their potential effect on other beneficial uses of the Bay and especially upon the marine ecology of Westernport. In its present form, the model provides a first step towards a total ecosystem model of Westernport Bay.

Use of the model to date has been restricted to application of the hydrodynamic and pollutant transport components. Good agreement has been obtained between predicted and measured values of tidal heights and velocities. The model has also yielded some previously unsuspected transport patterns, especially at the western entrance of the bay; these results have important management implications and suggest the need for additional field measurements to verify both the model and the predictions.

The development of the model is related to existing 'water quality' and 'ecosystem' modelling approaches. General mathematical relationships are used to define the present strengths and weaknesses of the model and to indicate profitable directions for future model developments and data collection programs.

INTRODUCTION

A model is a representation of a real system which can be used to make predictions which can be tested. If a model is incapable of prediction, it is of no interest to resource managers; if it is incapable of verification, it may still be of interest but the conclusions drawn from its use will be severely limited.

Many different types of models have been developed to predict the impact of human activity on the physical, chemical and biological condition of estuaries. Good agreement has been obtained between predicted and measured values of physical variables such as water movements: these variables are sensibly independent of the chemical and biological components and the physical laws governing their behaviour and interaction are well understood. The calibration and verification of chemical and biological system components, however, is still at a relatively early stage of development, due primarily to the lack of understanding of the complex physical, chemical and biological interactions which occur in marine ecosystems.

The Westernport Bay Water Quality Model has been developed as a first step towards a total ecosystem model for Westernport. The following sections of the paper outline the present structure of the model, some results obtained to date from its use and proposals for future extension and application of the model.

WESTERNPORT BAY WATER QUALITY MODEL

The model includes all waters of Westernport Bay with the boundaries defined by the high water mark, river entrances and sea entrances as shown in Fig. 1. To provide accurate boundary conditions, the model extends seawards beyond West Head, Nobbies, Red Point and Griffith Point. The model boundaries can be readily changed to include, for example, the sea adjacent to the MMBW south-eastern outfall at Boags Rock.

Model Structure

The model comprises a number of computer programs which may be run either independently or as an integrated suite. These programs solve the basic equations of fluid flow and chemical kinetics at each of the thousand or more grid

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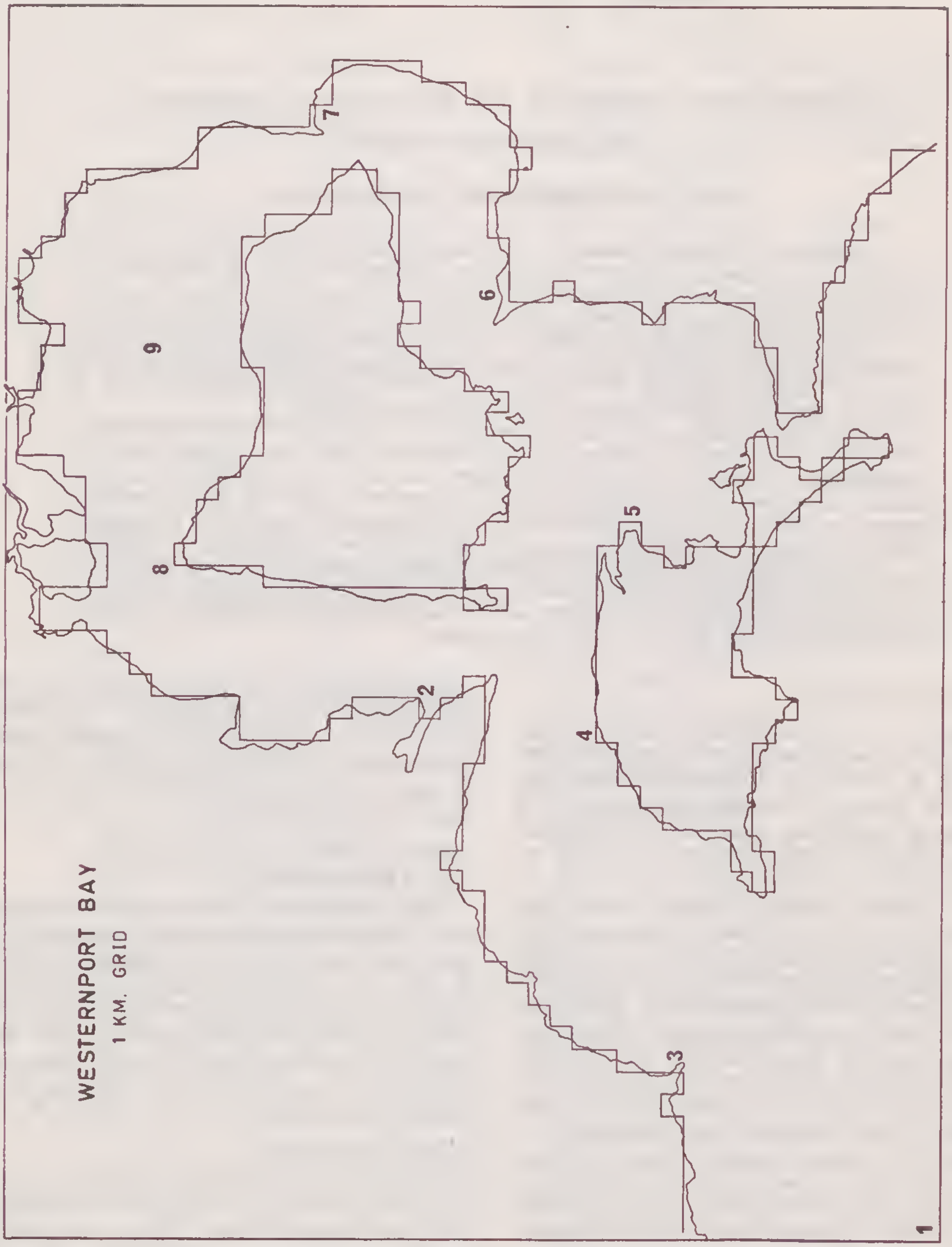

FIG. 1—Model boundaries.

points throughout the Bay. The principle programs are shown in Fig. 2 and are described below.

The first program in the sequence is the *Topographic Program* which accepts data on water depths obtained from charts or other survey information. The program applies a weighting procedure to these values to produce depth values on a grid selected by the user. This information is stored on disc or magnetic tape for use in later stages of the computations. A valuable feature of the program is that depth values may be continually updated by reading in new values over any or all of the field.

The *Hydrodynamic Program* is used to compute tide heights and current velocities throughout the Bay. This program is a derivative of that devised by Leendertse in which the depth-integrated equations of motion are solved numerically by a mixed implicit-explicit method, a procedure which ensures numerical stability. It has been adapted to the geometry of a bay which includes islands, more than one entrance to the open sea and mud flats which dry and flood. The equation is two dimensional, reproducing variations in the horizontal directions but not in the vertical direction: the data presently available on Westernport Bay show that vertical stratification is unimportant, except in very localized areas. Hence this model can be expected to be quite reliable throughout the Bay, except in small channels and at the edge of the mud flat region.

The procedure adopted in the *Pollutant Transport and Chemical Kinetics and Interaction Programs* to calculate the movement of a conservative pollutant is to release computational 'particles' at points in the grid system so as to simulate an effluent discharge. The number of particles introduced at each time interval gives the time variation of the discharge being simulated. At each time interval each particle is moved

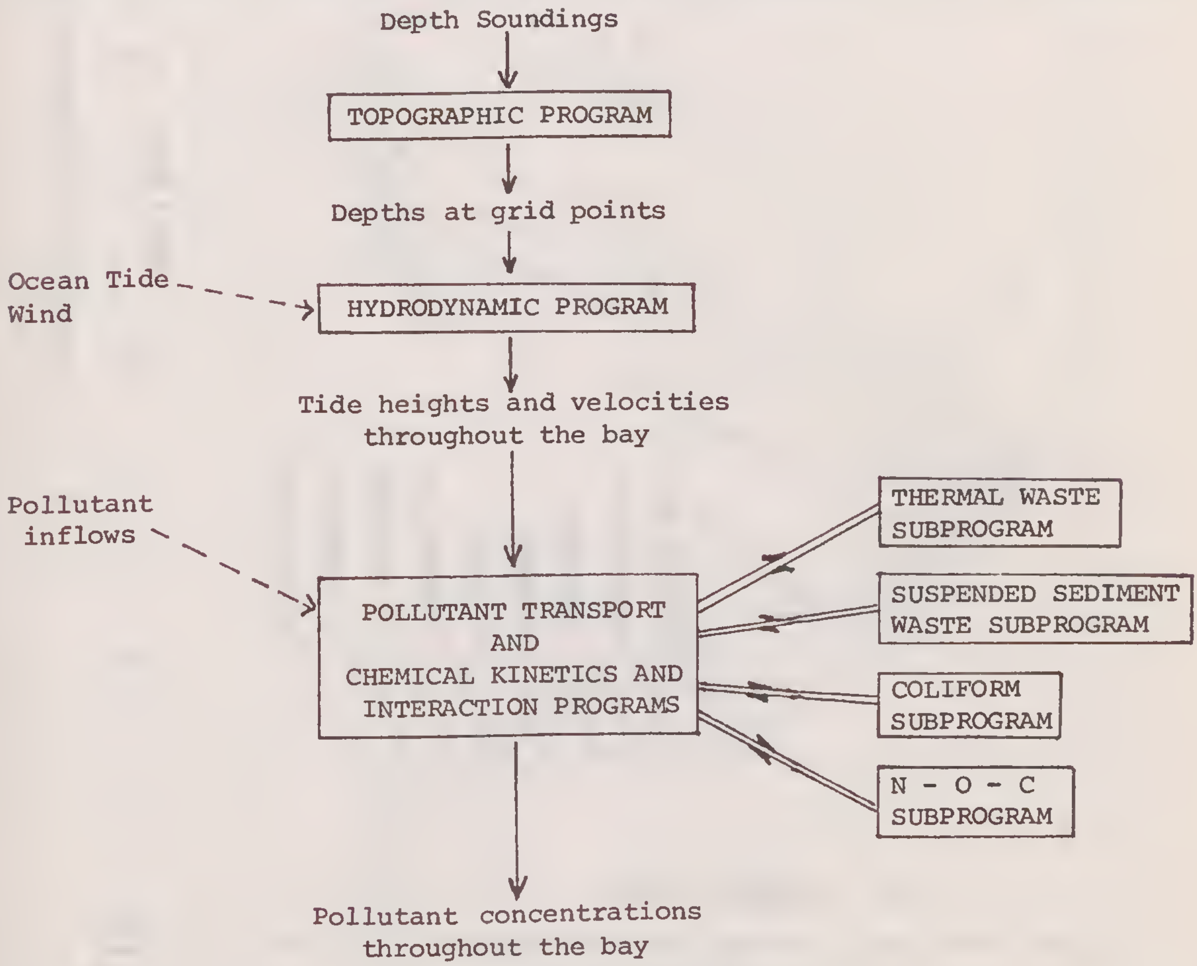

Fig. 2—Structure of Water Quality Model of Westernport Bay.

FIG. 3—Computed tide curves, Westernport Bay.

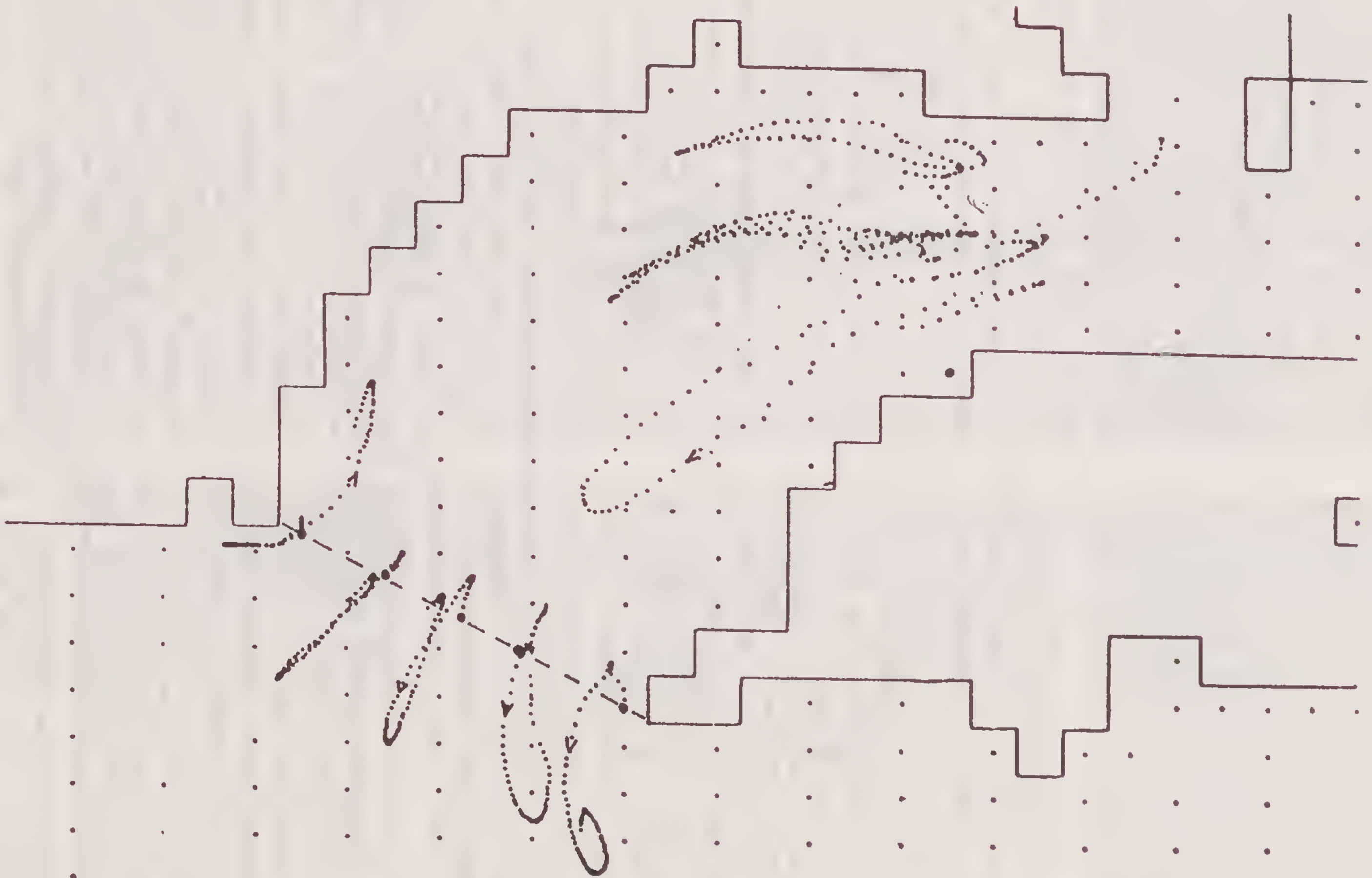

FIG. 4—Computed trajectories of particles released near slack water on a flood tide and tracked for One Tide Cycle.

a distance in the direction of the tidal velocity at that point equal to the tidal velocity multiplied by the time interval. To this movement is added a random step whose envelope is an ellipse, the axes of which are determined by the dispersion characteristics of the flow. The random walk of the particles accurately reproduces the dispersion due to turbulence and velocity shear. At any time subsequent to the release of the computational particles the resultant spread or relative density of the particles in the grid allows a direct determination of concentration contours. The advantages of this direct simulation of the dispersion process have been demonstrated by Pollock and Maier-Reimer.

A relatively simple modification for a pollutant which decays with time would be to reduce the number of particles present at each time according to the decay law. However, this would require the release of a vast number of particles to give the desired accuracy, and so a more economical solution is to reduce the quantity of pollutant represented by a given particle as the pollutant decays. In the *Thermal Waste Subprogram* the quantity of excess heat carried by a computational particle is reduced by evaporation, radiation and conduction to the atmosphere as the particle is advected by the local mean velocity and is randomly displaced by the dispersive processes. Similarly, in the *Suspended Sediment Waste Subprogram* the sediment is deposited when the velocity falls below a locally evaluated threshold value. Each of these subprograms represents a compromise between a complete analysis of the behaviour of the pollutant, involving variations in concentration with depth with consequent dynamic effects, and the increased cost and time of development of reliable models of these complex processes.

The remaining subprograms shown in Fig. 2 compute the change in levels of oxygen, the various states of nitrogen, organic carbon and coliform bacteria. The levels of these quantities depend on the temperature and natural reaeration and oxygen demand. Radical departures from the present conditions will change these factors and will require that new values be estimated. It is tempting to try to predict these changes by use of a mathematical model of the biology and biochemistry of the Bay, and this is the next model extension that the authors hope to develop.

Model Calibration and Application

The development of all programs shown in Fig. 2 has now been completed. Calibration of these models against field data has also been completed, except for the Chemical Kinetics and Interaction Program for which appropriate field data are not yet available—and indeed for some states, such as anaerobic conditions, should never become available if the Bay is properly managed.

The major application of the model to date has been in the use of the Hydrodynamic Program to investigate water movements under various tide and wind conditions. This information has also been input to the Pollutant Transport Program to investigate the movement of conservative pollutants under the same tide and wind conditions.

Fig. 3 shows a set of tide curves obtained from the model for the M2 tide, no wind condition, with the Bay assumed to be initially stationary at low water level. The increase in tidal range and lag towards the head of the Bay agrees with measured data.

The trajectories of two groups of particles, released just before slack water on the flood tide, are shown in Fig. 4. The particles have been 'tracked' for a little longer than one full tide cycle. Two features of particular importance to the flushing of the Bay are shown by particles released on the line across the Western Entrance. First, near Seal Rocks on the eastern side, particles which have run out on the ebb do not return on the flood tide and hence are flushed from the Bay. Secondly, near Flinders on the western side, particles have run in much further on the flood than they ran out on the ebb tide. Hence fresh sea water is entering the lower part of the Bay along this shore. This model prediction has not been tested by field measurement of velocity, but limited chemical sampling shows that the water along that shore bears more affinity to the water of Bass Strait than does the water on the eastern side, which is essentially 'bay water'.

This prediction illustrates an important use of the model: to define or discover problem areas which may be studied in the field, avoiding expensive and time-consuming general field studies and enabling resources to be concentrated on important areas and variables.

Future runs of the model will include an investigation of the behaviour of non-conservative pollutants and extension of all preceding studies to investigate the hydraulic and biochemical consequences of changing model parameters such as boundaries (to simulate reclamation, construction of causeways, etc.), depths (dredging) and levels and locations of pollutant inflows.

ECOLOGICAL MODELLING OF WESTERNPORT BAY

During the last few years, ecological modelling has become one of the 'growth' areas of mathematical modelling. Simulation models of varying

complexity have been developed for many different types of ecosystems (Patten). Calibration and verification of these models remain difficult problems but the data base is slowly being expanded as new laboratory and field evidence is accumulated.

We can usefully distinguish two different approaches to the development of ecological models for marine ecosystems such as Westernport Bay: a 'water quality' approach which has evolved from the early studies of the BOD–DO relationship, studies associated with such names as Streeter and Phelps, and an 'ecosystem' approach (of much more recent origin) which has attempted to model mass and energy flows through complete ecosystems. Recent papers which exemplify these approaches are those by Thomann et al. and Kelly. Both approaches have their advantages and disadvantages and both are relevant to Westernport Bay: the 'water quality' approach is simpler to develop and calibrate, but does not internalize the biological interactions on water quality, nor does it yield information on the output levels and behavioural response of the variables of ultimate interest to resource managers, e.g. fish populations; the 'ecosystem' model, on the other hand,

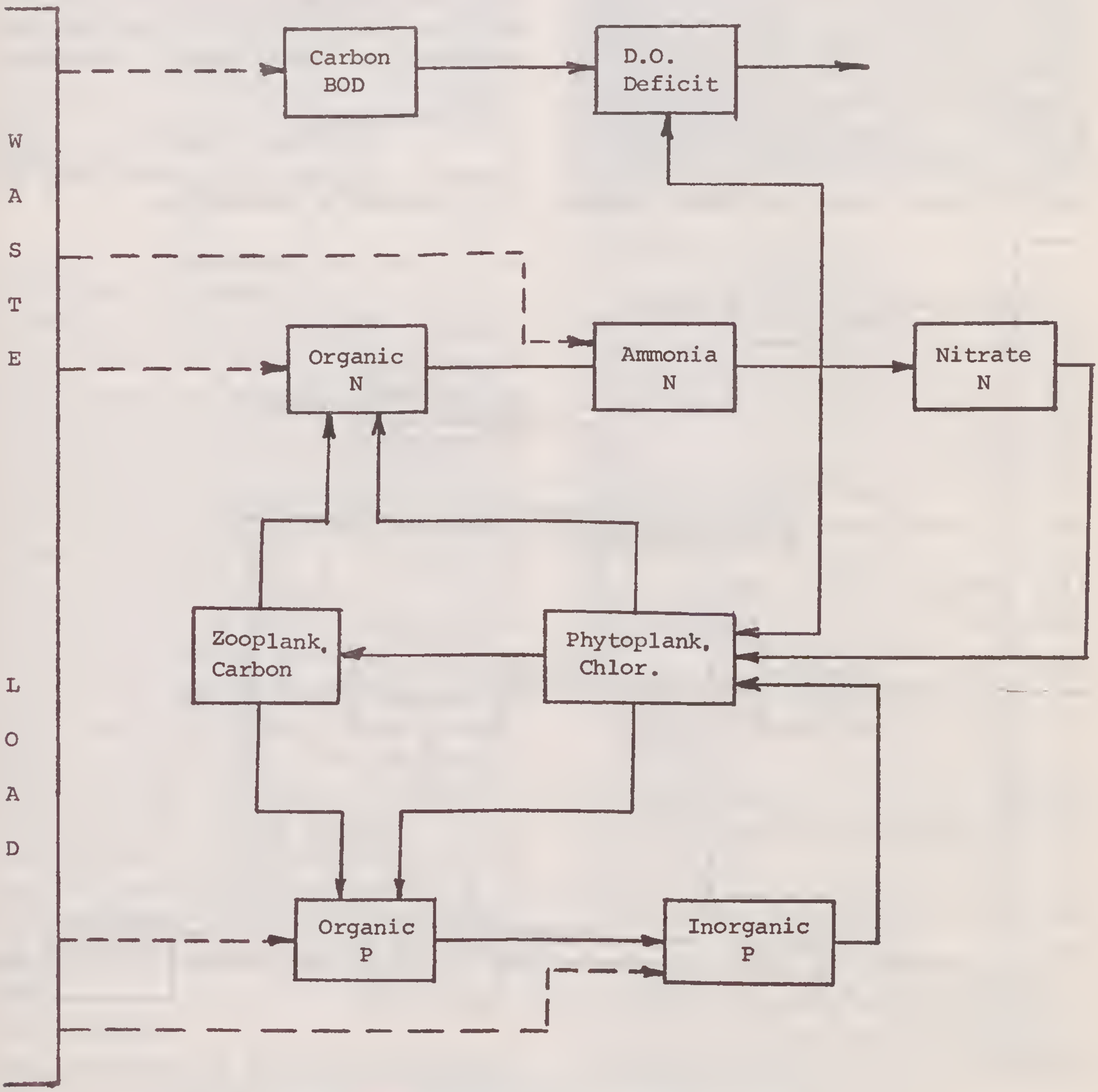

FIG. 5—Phytoplankton Model—Potomac Estuary (Thomann et al.).

includes more relevant variables and, at least in principle, can provide explicit information on all significant management variables. Much more information must still be obtained on both biotic-abiotic and chemical-physical interactions before the latter models can be transformed from concepts into reliable management tools.

The development of the Westernport Bay Water Quality Model, described in the preceding section, has followed the 'water quality' approach outlined above and attention is now being given to an extension of the model (along the lines of Thomann's recent work on the Potomac Estuary) to predict the dynamic behaviour of phytoplankton in Westernport Bay. Thomann's model is illustrated in Fig. 5, and comparison with Fig. 6 (representing the water quality component of the Westernport model) shows that the variables to be added to the Westernport model include the organic and inorganic phosphorus components, phytoplankton chlorophyll and zooplankton carbon. The present Westernport model includes introduced suspended sediment, bulk heat and coliform bacteria, components which are not included in the Potomac model.

The mathematical relationships involved in these 'water quality' models can be illustrated briefly by consideration of the basic relationship for conservation of mass of phytoplankton chlorophyll. For a water body of n segments (each segment being assumed completely mixed), we can write (after Thomann):

$$V \frac{dP}{dt} = AP + VS_p \qquad (1)$$

where V = segmental volumes (n x n diagonal matrix); P = chlorophyll concentrations (n x 1 vector); A = advective and dispersive transport coefficients (n x n matrix); and S_p = sources and sinks (n x 1 vector).

For water segment, j:

$$S_{pj} = (G_{pj} - D_{pj})\ P_j \qquad (2)$$

where G_{pj} = growth rate of phytoplankton; and D_{pj} = death rate of phytoplankton.

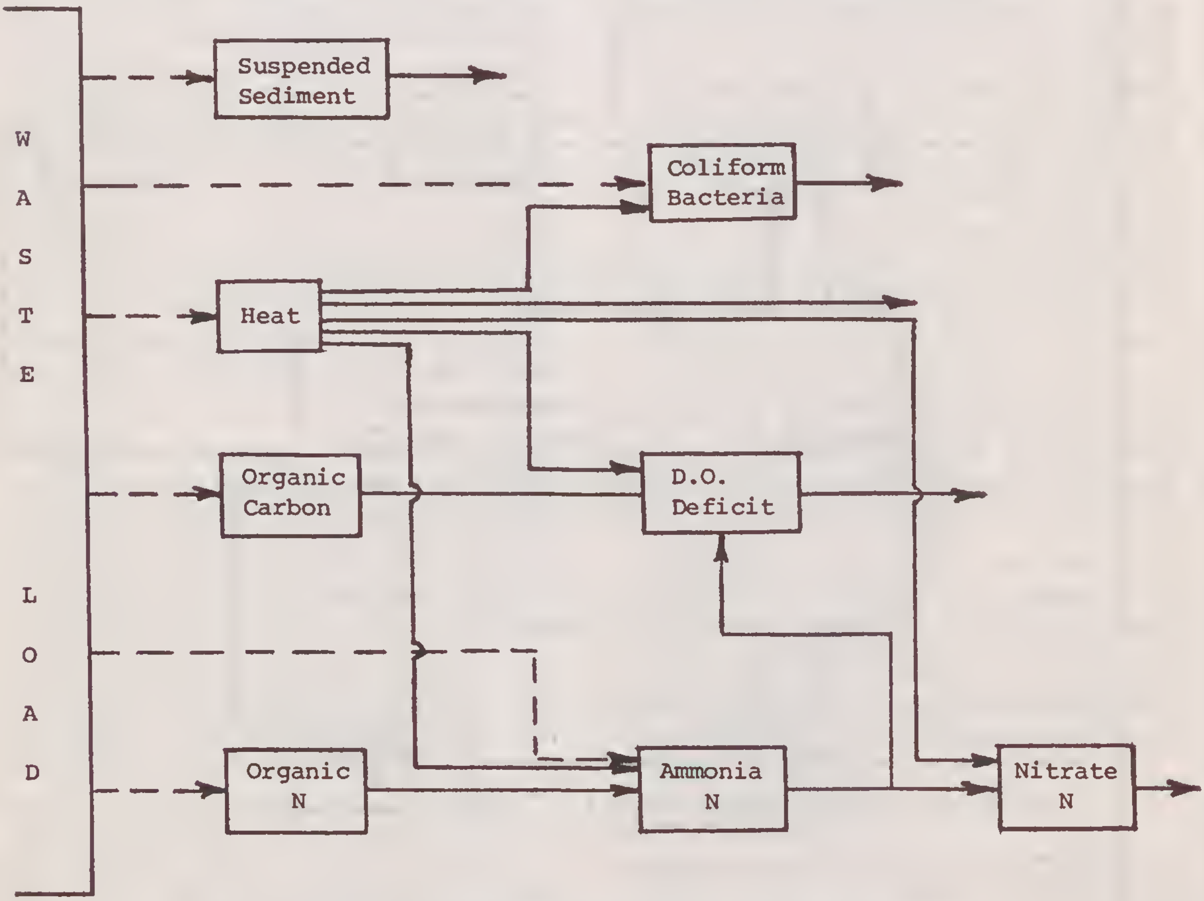

FIG. 6—Water Quality Model of Westernport Bay.

For the growth rate, the light and temperature effects and the Michaelis interaction effects of nitrogen and phosphorus concentrations are given by:

$$G_{pj} = G_{It}\ (I,T,f,H,K) \quad \frac{N_{In}}{K_{mn} + N_{In}} \quad \frac{N_{p2}}{K_{mp} + N_{p2}} \qquad (3)$$

where N_{In} = total inorganic nitrogen with K_{mn} as Michaelis constant: N_{p2} = orthophosphate concentration with K_{mp} as Michaelis constant; G_{It} = function relating growth rate and solar radiation, I, water temperature, T, photo period, f, depth, H, and light extinction coefficient, K.

Similar equations for conservation of mass in each of the other components of the model yield a set of simultaneous, nonlinear, ordinary differential equations for each segment. When these equations are aggregated for all segments we obtain the following equations for the whole water mass:

$$V \frac{dC}{dt} = AC + VS_C \qquad (4)$$

where C = a generalized concentration vector (n x number of compartments).

Equation 4 offers a very useful summary of the present status of the Westernport Bay Water Quality Model. The first term on the right-hand side represents a set of *linear* equations, each of which relate the concentrations of a particular compartment (e.g. phytoplankton chlorophyll) in the n segments of the water mass. These segmental concentrations are coupled to each other through the A matrix, which represents the time-dependent transport interactions. The basic hydrodynamic and transport models used in the Westernport model simulate these interactions in a more accurate manner than previous modelling efforts and this work should not need further refinement.

The second term on the right-hand side of Equation 4 represents a set of *nonlinear* equations, each of which relate the concentrations of phytoplankton, zooplankton and nutrient compartments within each water segment. As indicated above, these relationships are still in an early stage of development and current modelling and data collection efforts are being directed towards their more precise definition. Future extensions of the model will include the addition of the important detritus chain in Westernport Bay, as a further step towards a more complete definition of this term.

CONCLUSION

The Westernport Bay Water Quality Model has been briefly described and some preliminary results from the use of Hydrodynamic and Pollutant Transport programs have been presented. Good agreement has been obtained between predicted and measured tidal heights and velocities. The model has yielded some previously unsuspected transport patterns, especially at the western entrance of the Bay; these results have important management implications and suggest the need for additional field measurements to verify both the model and the predictions.

Two different approaches in ecological models for marine ecosystems are reviewed: a 'water quality' approach which has evolved from several decades of public health engineering, and more recently, an 'ecosystem' approach which attempts to model mass and energy flows through complete ecosystems. The development of the Westernport model is related to these approaches and general mathematical relationships are used to define the present status and future development of the model towards a complete ecosystem model of Westernport Bay.

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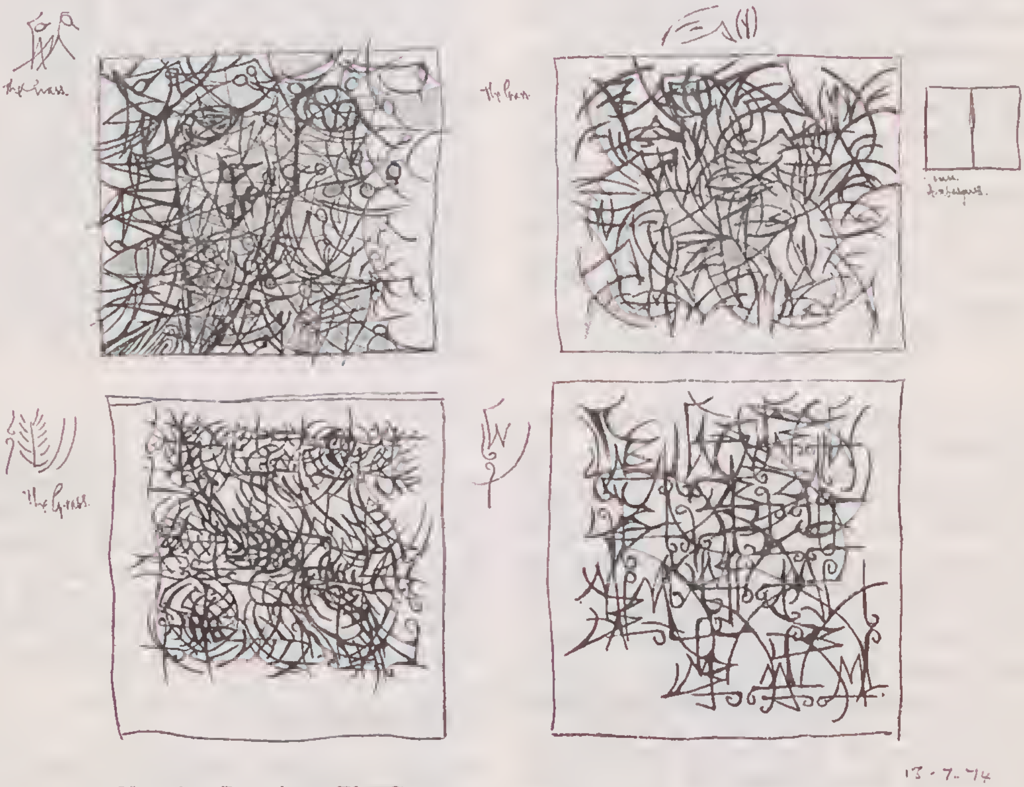

Notation Drawings: The Grass